19. SYNCHRONIZATION

INTRODUCTION

Synchronization between the sample excitation signal and the arrival of the x-ray probe pulse results in stringent timing and stability requirements. For excitation pulses of order 50 fs, and x-ray pulses of similar duration, the synchronization between pulses should be of similar magnitude, 50-100 fs.

Two time regimes may be invoked in discussing synchronization issues - *fast* jitter on a pulse-to-pulse timescale, and *slow* jitter occurring over a timescale of many pulses.

Feedback techniques may be applied to stabilize and control the accelerator on both of these timescales. A highly stable master oscillator and timing signal distribution system can be used to phase-lock all lasers and rf systems, minimizing jitter between the emitted x-ray pulse and the sample excitation laser pulse. *Fast* feedback systems operate around the accelerator rf structures to control timing (via phase feedback in rf structures for example) on short timescales. *Slow* feedback is derived from the timing error between the x-ray pulse and the experimental excitation pulse, measured at a beamline endstation, and this signal is transported to the *fast* systems to update setpoints.

Optical signals from synchrotron radiation produced by the electron bunch have the potential to provide an accurate signal with respect to the emitted x-ray photons. Selecting a beam-derived optical pulse from an arc prior to the x-ray production section would allow a time of some μs to transport and manipulate the optical pulse before the x-ray pulse arrives at the beamline endstation. This may allow the beam-based optical pulse to seed lasers at the beamline endstations, or to trigger other processes. While this may be seen to have advantages, the production of optical pulses of time duration ~ 100 fs requires special techniques to compress the synchrotron radiation pulse from the relatively long electron bunch of picosecond duration.

It is likely that a combination of both accelerator control and beam-based signal approaches will produce the most stable facility.

MASTER OSCILLATOR

As described in Chapter 17-Lasers, the Master Oscillator is a passively modelocked femtosecond laser cavity providing optical pulses of less than 100 fs duration. In essence, this laser is a highly stable comb generator. By illuminating a photodiode with output pulses from this laser, one can generate RF harmonics extending from the fundamental oscillator frequency (cavity frequency = 81.25 MHz, round trip time = 12.3 ns), up to the bandwidth limit of the photodiode (which can extend well into the GHz range). Thus, this laser is a direct source for all the necessary RF signals for the linac. Because the laser is passively modelocked, the phase noise is substantially lower than that of conventional RF oscillators at frequencies above ~1 kHz. The dominant phase noise contribution for such lasers originates typically from mirror motion due to environmental acoustics as well as amplitude noise of the pump laser [1-3]. With advances in stable diode-pump sources, pump laser effects can be largely eliminated [e.g. Coherent Verdi and Spectra Physics Millenia models]. In addition, air turbulence effects are eliminated in hermetically sealed cavities, and in modelocked fiber lasers [4,5], both of which are available from commercial vendors [e.g. Coherent Vitesse and IMRA America Femtolite models]. Low frequency acoustic effects and long-term cavity drift can be effectively suppressed by locking the fundamental cavity frequency to a conventional high-stability rf generator [1]. This is accomplished by constructing a phase-locked loop as illustrated in Fig. 19-1, in which the laser cavity acts as a voltage-controlled oscillator by modulating the cavity length with a moving mirror attached to a piezoelectric transducer. Thus, a femtosecond laser phase-locked to a stable rf generator provides phase noise levels which match that of the rf generator at low frequencies (DC to ~1 kHz), and are substantially better at high frequencies. Table 19-1 summarizes the essential characteristics of the Maser Oscillator laser.

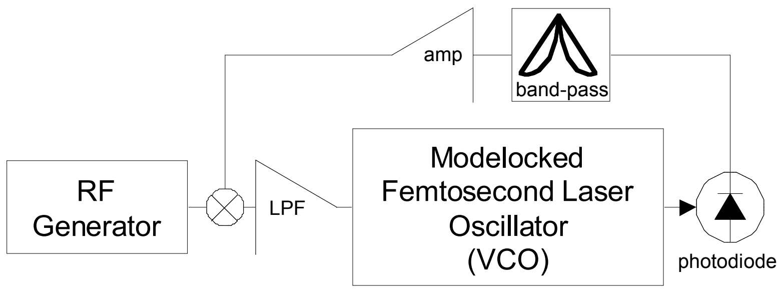

Figure 19-1 Master Oscillator for the recirculating linac source.

Table 19-1 General technical specifications for the Master Oscillator.

Master Oscillator Laser	
pulse duration (fs)	<100
wavelength (μm)	0.78 (1.55)
repetition rate (MHz)	81.25
average power (W)	~1
phase noise	<120 dBc/Hz

TIMING DISTRIBUTION SYSTEM

The optical distribution system must be extremely stable, particularly with respect to path length drift (e.g. a path length drift of only 10 μm corresponds to a time shift of 30 fs). One approach is to use free-propagating beams and mirrors. In this case, pointing stability will require an active position feedback system and hermetically sealed (low vacuum) optical transport lines. A second approach is to use a fiber delivery system. With either approach, active monitoring of the path length stability is asssumed. This may be accomplished by back-reflecting a portion of the pulses from the Master Oscillator to provide a path-length reference. Alternatively, a cw reference laser may be used with interferometric techniques to monitor and control the path length.

One advantage of an optical fiber delivery system is that it completely eliminates any pointing stability problem. However, in a fiber delivery system the nonlinear optical effects and pulse-stretching effects (group-velocity dispersion) must be managed. Nonlinear optical effects may be managed by propagating sufficiently low pulse energies. Group velocity dispersion may be managed by using photonic bandgap fiber in which the group velocity dispersion is balanced by the modal dispersion [6]. Alternatively, by choosing a fiber laser operating at 1.55 μm as the Master Oscillator laser, one can take advantage of zero-dispersion fiber that is routinely used for telecommunications applications.

Figure 19-2 illustrates the general layout of the timing systems. The overall timing for the machine is determined by the Master Oscillator which consists of a passively modelocked femtosecond laser oscillator coupled to a high-stability rf generator. The Master Oscillator is the original source for the rf signals required for the linac as well as the original source of seed laser pulses for laser amplifiers at various beamline endstations. The photocathode drive consists of a second laser system (oscillator/amplifier combination) that is slaved to the Master Oscillator. Laser pulses from the Master Oscillator are distributed via an optical transport system to various beamlines. These pulses may be amplified directly at the beamline endstations in order to create laser pulses for sample excitation. Alternatively, seed pulses from the Master Oscillator may be effectively re-generated at the beamline endstations by using a separate modelocked femtosecond laser oscillator (synchronized to the Master Oscillator), followed by a power amplifier.

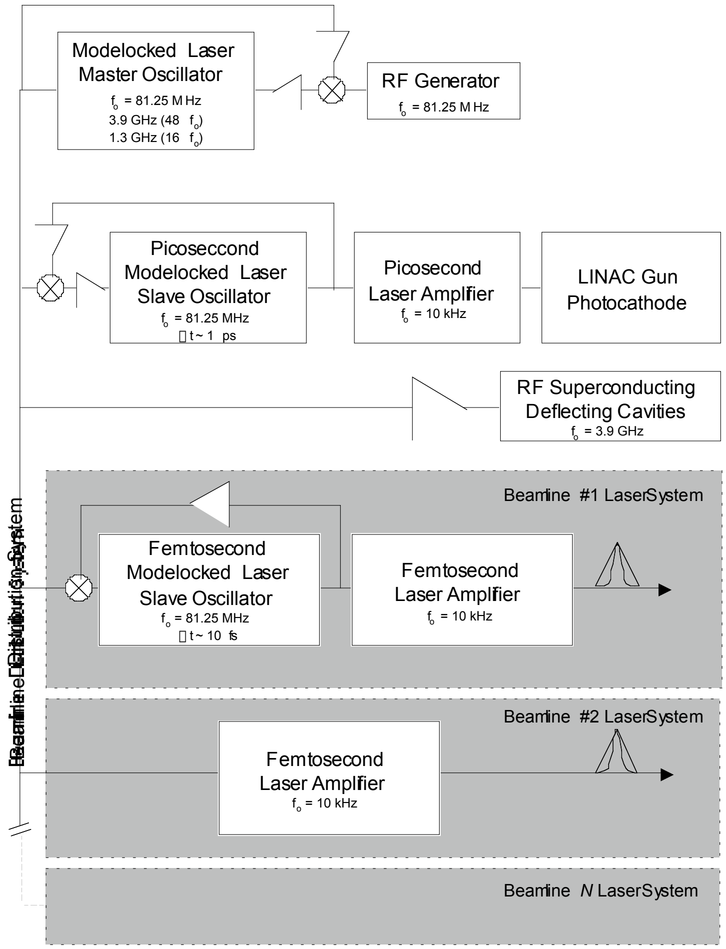

Figure 19-2 Schematic layout of the timing systems.

Delay Lines and Path Lengths

The path lengths from the Master Oscillator laser to the various beamline endstations will in general not match the path length of the electron beam and x-rays. Thus, delay lines will be required. These delay lines should be as compact as possible and the length kept to a minimum (~1 m) in order to preserve stability. An important point is that the Master Oscillator laser acts as an extremely stable optical delay line. Beamline users can select any pulse, within a given time window (from the 81.25 MHz train of pulses) for subsequent amplification and sample excitation. This timing accuracy can be understood by considering a time window on the order of 1 μsec. Such a long temporal window should easily encompass any path length discrepancies between laser pulses and x-rays. In such a time window (corresponding to 1 MHz frequency) the motion of the laser cavity mirrors is negligible as illustrated by the following estimation. In 1 μsec the pulse in the Master Oscillator laser cavity will undergo ~81 round trips. To maintain a timing accuracy of 30 fs, we require that the integrated path length variation (during the 81 round trips) not exceed 10 μm, or 0.12 μm per round trip on average. Mirror motion of 0.12 μm within the 12.3 nsec round-trip time corresponds to a mirror velocity of 10 m/sec, which would require a force well beyond anything that could be generated from acoustic disturbances or from the piezoelectric transducer.

DEFLECTING CAVITIES

Our scheme of manipulating the electrons followed by optical pulse compression carries the advantage of providing insensitivity of the x-ray pulse timing at the sample following the crystal optics, to the arrival time of the electron bunch in the deflecting cavities. An electron bunch arriving "synchronously" with the deflecting RF voltage will experience a transverse kick of equal amplitude and opposite direction to the head and tail electrons. Electrons in a bunch arriving early or late with respect to the deflecting voltage zero phase will receive a similar transverse kick dependent on their position within the bunch, but the bunch also receives a net offset kick and the centroid will oscillate afterward. Since the bunch duration is short compared to the rf period (3.9 GHz deflecting cavities), the transverse kick to electrons within a bunch remains linear with the same slope. Figure 19-3 shows the perturbation to the electron bunch in the deflecting cavities, resulting in time-position-angle correlation.

In the x-ray crystal optics, the optical path length varies linearly with transverse position on the crystal, and early or late bunches produce radiation that will receive proportionately longer or shorter delays in the optical path, thus remaining synchronous with the deflecting cavity rf phase. Following the asymmetric crystal optics, the time of arrival of the x-ray pulses is the same regardless of the jitter in arrival time of electron bunches at the deflecting cavity. In this way, the temporal jitter of the electron beam is transformed into spatial jitter of the x-ray pulse. Figure. 19-3 gives a pictorial view of this scheme.

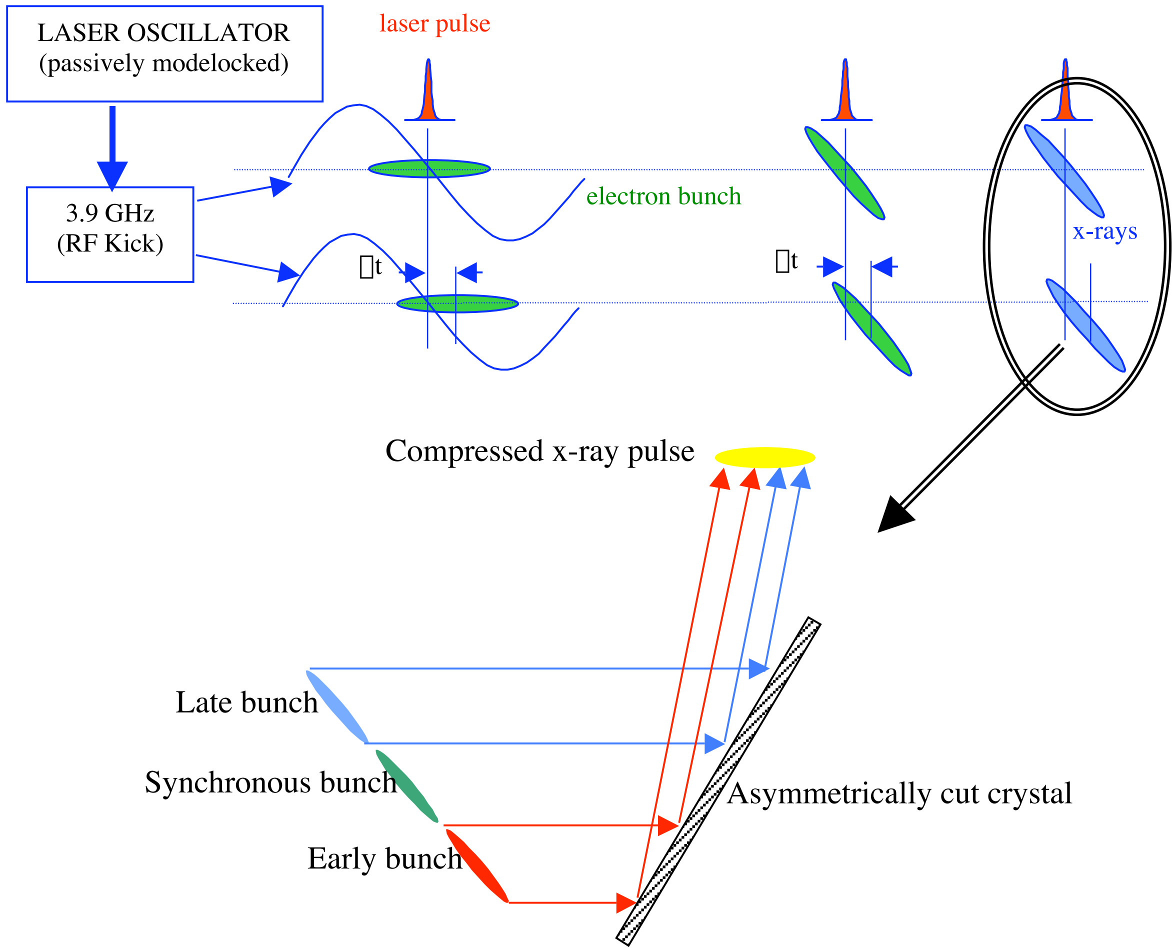

Figure 19-3 The hard x-ray production scheme, showing the electron bunch in the deflecting rf field with different arrival times with respect to the cavity phase. Bunches arriving early or late in the cavity still experience a distribution of particles in alignment with those of a bunch arriving in phase with the cavity field. X-rays from such bunches experience the same compression in the x-ray optics, resulting in improved timing stability, but with a geometric translation of the x-ray pulse on the sample.

Low-level rf system for the superconducting deflecting cavities

As described above, with the deflecting cavity locked to the laser oscillator, stability of the x-ray pulse will depend on the phase stability of the deflecting cavity voltage. The low-level rf system for the superconducting deflecting cavities is instrumental in determining the final synchronization between the beamline lasers and the femtosecond hard x-rays. The rf drive signal at 3.9 GHz is derived directly from the Master Oscillator via illumination of a photodiode and subsequent electronic amplification. Since the fundamental rf signal at its source is absolutely locked to the laser pulses from the Master Oscillator, maintaining this synchronization is largely an issue of feedback control of phase while minimizing the electronic noise from the rf amplifiers and isolating (or actively damping) the deflecting cavities from external acoustic perturbations.

A 10 fs timing error is equivalent to 0.014° in phase at 3.9 GHz, and we require control at this level. Resolution of 1 fs requires measurement to 2.44×10^{-5} rad, or one part in 41,000. A 16-bit DAC offers the required resolution. The system bandwidth of approximately 100 Hz allows ample time for signal processing.

The superconducting cavity has an external bandwidth requirement of approximately 100 Hz to allow feedback control of phase and amplitude required due to cavity resonant frequency perturbations arising from microphonically induced changes in cavity geometry.

A photodiode or similar optical-electrical transducer illuminated by the Master Oscillator signal can be attached to an electrical band-pass filter at 3.9 GHz, to provide a stable drive signal. At least one isolation stage is needed, either low noise active or a circulator, before this signal is used for measurement and control of cavity fields. Figure 19-4 shows a schematic of the deflecting cavity rf system electronics.

Designing for low jitter really means designing for low noise. Over time spans of 10-100 ms (100 to 1000 pulses), temperature changes and 1/f effects become important, and timing error between the x-ray pulse and the experimental excitation pulse, measured at a beamline endstation will provide a (digital) correction signal for cavity phase over this time period. The cavity control system only has to keep the accelerator stable long enough to get good signal/noise out of the pump laser/x-ray pulse relative timing measurements, and for those results to propagate through networks and software filters to update the digital setpoints.

Numerology of the timing frequencies is important. A simple integer scaling from the Master Oscillator to RF frequencies is probably bad, as that places the output of the mixers at DC. Quarter integer scaling places the output frequency at about 20 MHz for both the 1.3 and 3.9 GHz cavities, which would provide traditional I/Q/-I/-Q output from an 80 MSample/s ADC. Figure 19-2 shows the deflecting cavity rf system schematic diagram.

Although 16-bit 80 MSample/s ADCs do not exist at the time of writing, currently available parts (AD6645, 14-bit, 75 dB SNR at 15 MHz and 80 MSample/s) come close enough to allow meaningful tests and future developments may be expected to provide for our requirements.

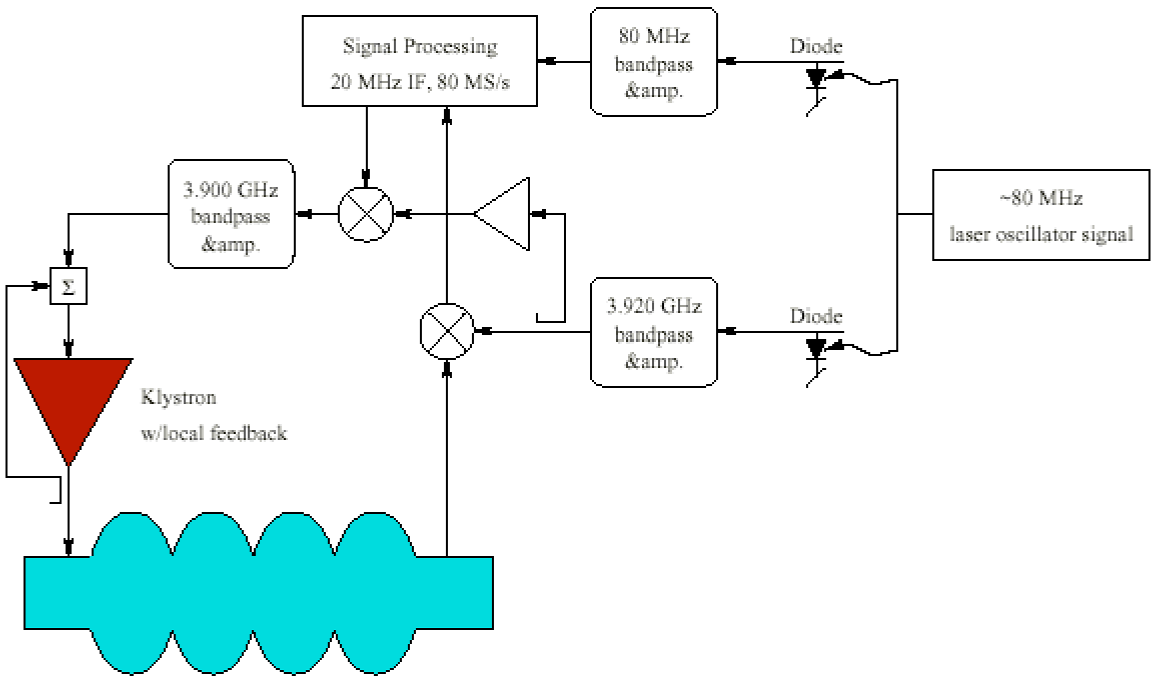

Figure 19-4 RF systems control schematic for the deflecting cavities.

We estimate the thermal noise in the system by assuming a room temperature (T) amplifier with 3 dB noise figure (NF) and 30 dB gain (G), bandwidth (Δf) 100 Hz. The noise power

$$P_{thermal} = k\,T\,\Delta f\,NF\,G \tag{1}$$

is then 8×10^{-16} W or 2×10^{-7} volts in 50 Ω (k is the Boltzmann constant). A 7 dB NF mixer would contribute significantly less noise. A resolution of 1 fs requires that the signal equivalent to a 1 fs phase change be greater than the noise level, and we find that the cavity signal amplitude must be greater than approximately 10 mV. Such a signal level may readily be obtained from a cavity probe. A similar analysis shows that thermal noise in the photodiode and rf drive chain is not expected to prove problematic.

Low-level rf system for the photocathode rf gun

Since the bunch compression scheme transforms energy jitter from the injector into timing jitter in the main linac, the launch phase of the electron bunches must be controlled to stabilize energy jitter to an acceptable level. While the rf signal derived from the Master Oscillator is expected to be stable to ~100 fs, a low-level rf system similar to that shown in Figure 19-4 may be applied to control the launch phase of the photocathode gun rf fields with respect to the photocathode laser pulse.

OPTICAL BEAM-BASED SIGNALS

Two concepts are shown here for measuring the slow changes in electron bunch timing with respect to the Master Oscillator. These signals may be used to update the setpoints for the fast feedback systems described above. In addition, optical signals produced by the beam may be used to seed experimental pump lasers.

The first concept involves preparing a ~100 fs optical pulse from the synchrotron radiation emitted in a dipole bend magnet of the photon production section. With the electron beam displaced as described in Chapter 1-Overview, the optical pulse may be compressed in an echelle reflection grating to provide a short-pulse timing signal. An optical correlation technique may be used to provide an error signal and update the fast feedback system setpoints. Figure 19-5 shows a schematic of the technique.

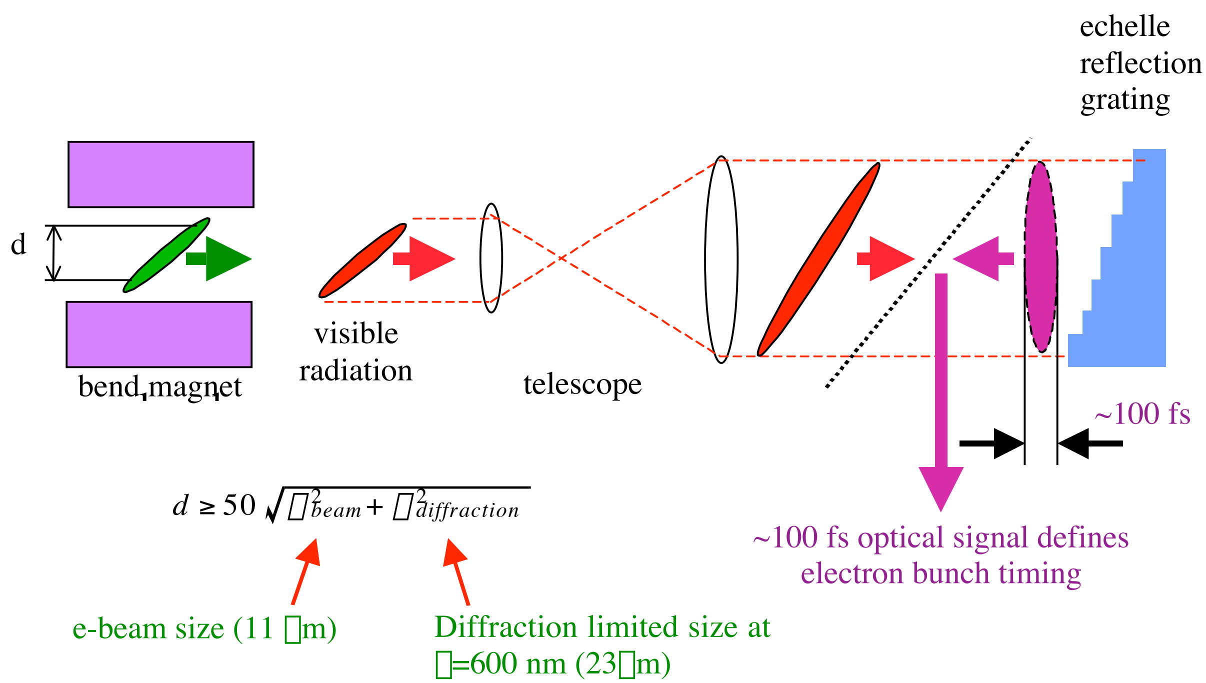

Figure 19-5 Concept for beam-based optical timing pulse production.

Another concept involves optical mixing of the synchrotron radiation pulse and a chirped optical laser pulse to provide timing information from the spatial position of the mixed signal from a crystal. A chirped laser pulse overlaps the short synchrotron radiation pulse, and the output signal detected on a ccd or similar array. The spatial position of the signal will be a function of the color of the laser pulse at which the short synchrotron radiation pulse enters the system, by virtue of the refractive index variation with wavelength. The concept is shown schematically in Figure 19-6.

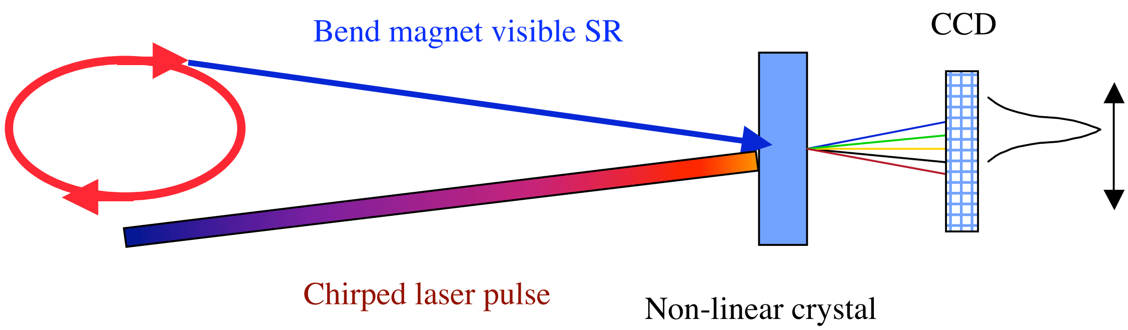

Figure 19-6 Concept for beam-based optical timing pulse production.

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